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IMPROVEMENTS IN THE 1978 "STANDARD" DUMAND MODULE: SEA URCHIN*

H. Hinterberger and A. Roberts
Fermi National Accelerator Laboratory, Batavia, IL 60510

and

F. Reines
University of California, Irvine, CA .

ABSTRACT

The following modifications are proposed to the 1978 Standard[1] array module:

1. Replace the benzyl alcohol WLS solvent by toluene[2] (with about 5% alcohol added). It is about one-eighth as expensive, has a density 0.90 at 500 atmospheres, and index of refraction above 1.50.

2. Replace the single 6m-long .33m-diameter cylinder by a large number of small cylinders - several hundred, of ca. 2-cm diameter,and about 3m long(depending on the attenuation length of light in the medium). These are all optically coupled to the surface of a spherical lens. At the center of the spherical lens is the hemispherical photocathode of a single PMT, between 5" and 8" in diameter.

3.The optical coupling to the spherical lens should probably be made at string deployment time, so that the cylinder array can be more compactly stowed for transport. This implies a flexible, rubber-like matrix, in which the ends of the cylinders are embedded, and means for stretching and affixing it in place on the surface of the spherical lens, after the string has been released from its canister.

Very significant improvements in both cost and performance are expected from these modifications.

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1. INTRODUCTION.

The 1978 "Standard" DUMAND array[1] is based on a wavelength-shifting sensor (WLS) like the one shown in Fig. 1. It is a cylindrical tube, 1/3 m in diameter and 6m long, filled with the WLS solvent. Originally this was benzyl alcohol, whose density at a depth of 5 km is 1.07, and whose index of refraction at that density is 1.55.

This module, while a great advance over earlier concepts, still suffers from several disadvantages. Most serious is its anisotropy. It is insensitive to light in the axial direction, and in other directions has a sensitivity roughly proportional to $\sin\theta$, where θ is the polar angle measured from the WLS module axis. The response is thus like that of a dipole antenna. This could be ameliorated by pointing the axes of different modules in different directions; but since the design contemplates running the supporti~~ cable through the module along its axis (see Fig. 1) this solution would offer difficulties.

Benzyl alcoholhas several disadvantages. One is its high cost, about $1/lb in large quantities at present. Another is its high density, which requires the provision of external buoyancy, an expensive item, to maintain the desired string tension.

2. DIMENSIONAL CONSIDERATIONS.

If we consider cylindrical WLS elements, the effective light interception area is the diameter of the cylinder times its length, times the sine of the angle made by the light ray with the cylinder axis (The latter factor is included in the calculation of "external efficiency.")

The PMT cathode area required depends, for fixed indices of refraction, on the cross-sectional area of the cylinder, as does also the volume. Both volume and PMT cathode area increase as the square of the diameter, while the light intercepted increases only linearly with it. Thus we minimize both PMT cathode area and solvent volume by making the cylinders as small in diameter as possible, and using many of them to obtain the required area for incoming light. The limit to this process is the use of fibers in the mm range or less. Such plastic fibers have been successfully used as scintillators. We will not pursue the miniaturization of the cylinders quite so far; there are serious problems of attenuation, surface quality, etc., to be solved. In addition, for very small diameters it may be difficult to provide sufficient absorption for the incoming Cerenkov light to absorb it efficiently in a very short distance. Concentrations of WLS high enough to achieve this are likely to have high attenuation for the fluorescent light as well.

We consider, rather, small tubes - probably of glass, which is inexpensive and less prone to diffusion as compared to plastics,

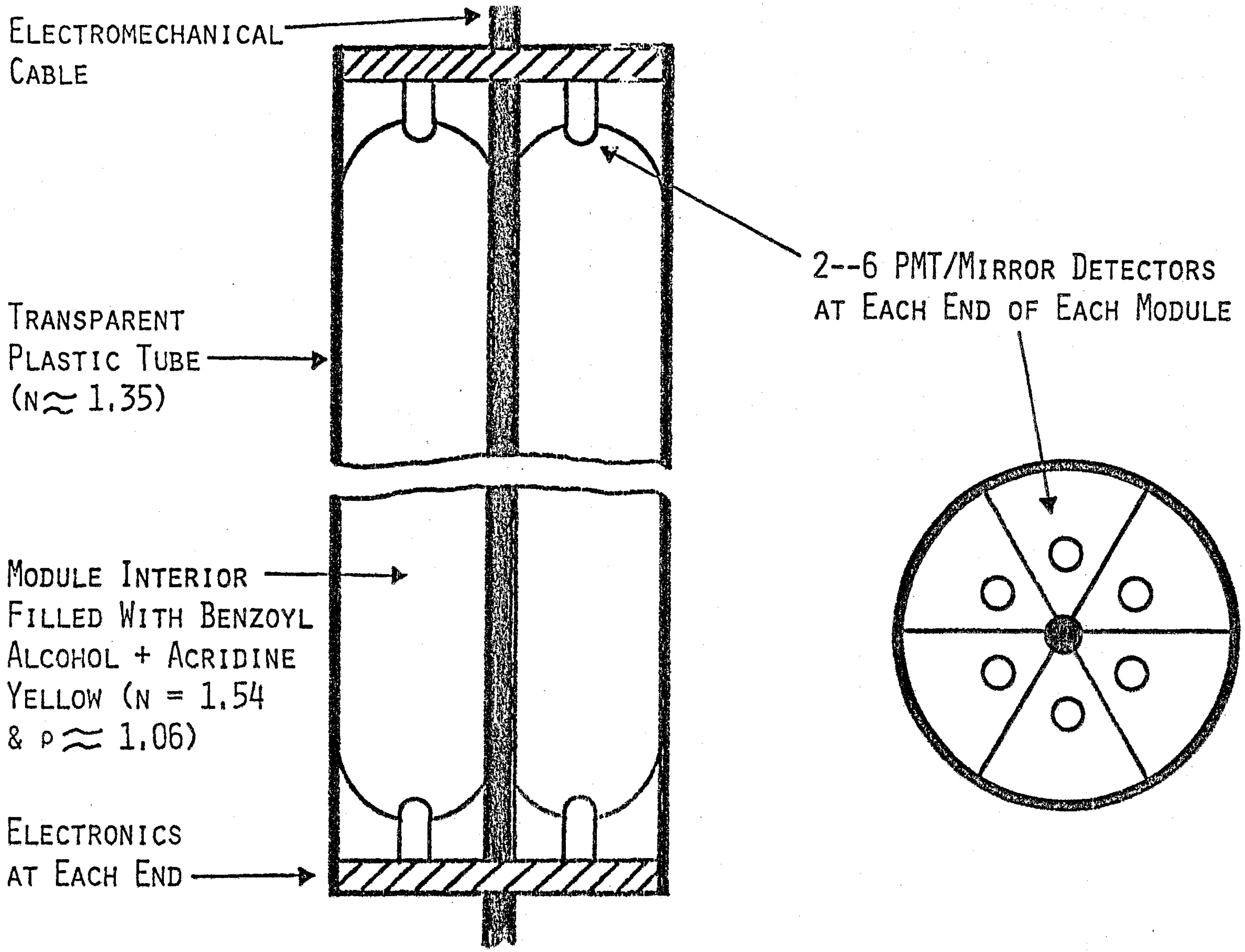


FIG. 1. LONGITUDINAL AND ORTHOGONAL CROSS SECTIONS OF A 1978 DUMAND OPTICAL SENSOR MODULE. NOTE END-TO-END SYMMETRY. MODULE DIMENSIONS ARE: LENGTH = 6.0 METERS; DIAMETER = 0.33 METERS; SPACING = 36.6 METERS.

as containers for the WLS solvent. We find that to obtain good overall sensitivity with a hemispherical PMT cathode of area in the range 250 - 500 cm^2 (5" to 8" diameter), tubes of diameter 2 cm or thereabout are needed. These are large enough to be conveniently handled, and not too fragile in lengths of several meters.

3. DESCRIPTION OF COMPUTER PROGRAMS.

In order properly to evaluate different designs, it has been necessary to write two analytical computer programs.

1. The program CYL2 is intended to evaluate the amount of light captured by total internal reflection in a cylindrical tube irradiated by Cerenkov light from outside, which contains a dissolved WLS so that each point on the interior is an isotropic source of re-radiated light. Allowance is made for attenuation of the fluorescent light, and for imperfect total reflection at the surface. Attenuation of the incoming Cerenkov light can also be included. Skew rays are also included. The program yields the fraction of the incident light reaching the exit pupil (the tube diameter at one end; the other end is assumed to be reflecting.) It also gives the angular distribution of the emergent light with respect to the cylinder axis. It does not presently include partial reflection of the incident light at small angles. Fig. 2 shows the angular distribution of the collected light in a 2-cm tube filled with toluene, immersed in sea water at 500 atmospheres.

2. The other program, CORONA, calculates , using CYL2, the fraction of a parallel beam of light that is intercepted by an axially symmetric array of independent cylindrical WLS elements, neglecting shadowing. To obtain isotropic response, an array of small cylindrical elements is preferable to a single large one. The isotropy is evaluated for a given array by varying the direction of the incident light. In the simple case of an array lying on the surface of a cone, there is a clear and narrow optimum range of cone angles centered at 45°. Such an array is isotropic to $\pm 3.5\%$; changing the angle to 30° or 60° makes the anisotropy almost ten times worse. Fig. 3 shows such a conical arrangement, which we have dubbed the Crown of Thorns.

The program does not include partial reflection of the incident light at the surface of the cylinder; it does include total reflection there, for the case in which there is an intermediate air-space between the ocean and the WLS cylinder (see below.)

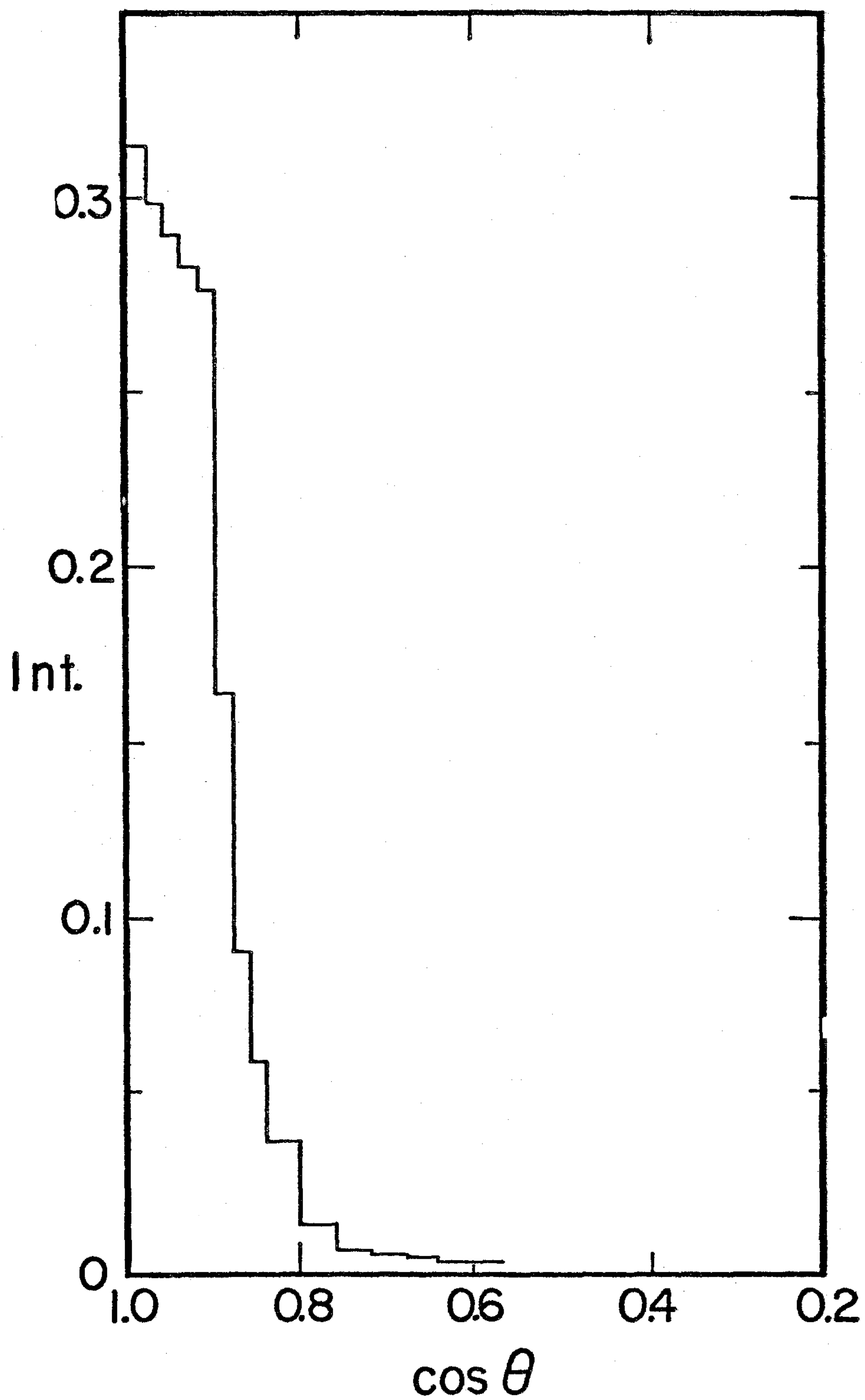


Fig. 2. Angular distribution of the light emerging from a 2-cm diameter tube, 1.5m long, with an attenuation length of 3m, and surface reflectivity .99. The tube is filled with toluene, n = 1.51, immersed in seawater, n = 1.35. We see that 83% of the light is contained within a cone of half angle 28.4° (cosθ = .88)

4. EVALUATION OF DOUBLE-WALL DESIGN.

We have also evaluated the case when there is an intermediate airspace between the ocean and the WLS tube, filled either with air or some other gas. Such an air space, which would have an index of refraction 1.14 if filled with air at 500 atmospheres, has two effects. It decreases the penetration of incident Cerenkov light into the WLS, especially in directions making a small angle with the cylinder axis. On the other hand, it increases markedly the efficiency of collection of the fluorescent light, because the difference of index between the solvent and the surrounding medium is increased. Evaluation of these effects shows that for normally incident light there is a net gain. Unfortunately, when the efficiency is evaluated at other angles of incidence, the net gain disappears when averaged over direction, becoming a large net loss.

This scheme has another, more subtle drawback. We would like to take advantage of the limited phase space of the internally reflected fluorescent light, in order to match it into the smallest possible PMT cathode area. The net gain of light provided by lowering the index of the external medium is not helpful in this regard; it collects more light, but does not increase the phase space density, and thus requires additional PMT cathode area.

CROWN OF THORNS

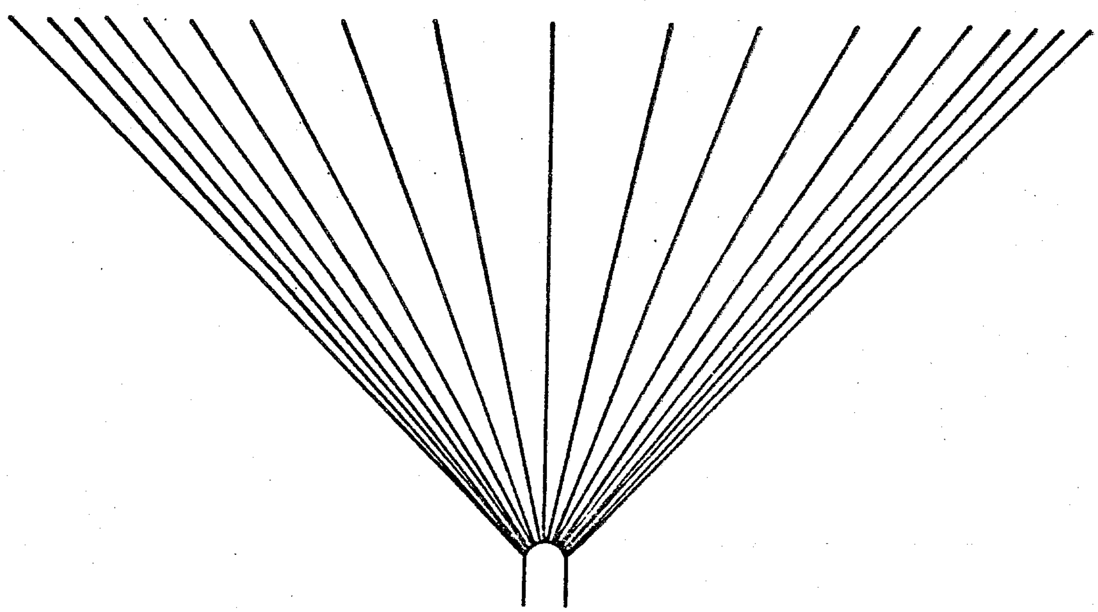


Fig. 3. Crown of Thorns array: 60 3m-long 2-cm diameter tubes arrayed on the elements of a 45° cone. Light collection not shown; it would be as in Fig. 4.

5. THE SPHERICAL LENS PHASE-SPACE MATCH.

The best detector configuration we have found to date makes optimum use of the limited phase space of the collected fluorescent light. It also allows the largest number of WLS elements for a given PMT cathode area.

The mechanism of phase-space matching by means of a spherical lens is shown in Figs. 4 and 5. Fig. 4, showing the geometry of radial light-collecting elements, spherical lens and concentric hemispherical PMT photocathode, makes clear why the new configuration has been given the name "Sea Urchin." It can be pictured as a generalization of the 45^o "Crown-of-Thorns" array, extended to both larger and smaller cone angles. Such an expansion maintains at least approximate isotropy, since the anisotropies of cone angles larger than 45^o are complementary to those for angles less than 45^o. The residual anisotropy is then due to unequal populations of these two areas.

In principle the spherical lens can be used to increase the effective space density (without, however, disturbing M, Liouville's repose) by filling it with a medium of high index of refraction, just as with microscopes using oil-immersion objectives. That avenue, which increases the outer radius of the lens (Fig. 4) for the same PMT diameter, allows more cylindrical elements for the same size PMT; it is limited by the need for the PMT window to have as high an index as the lens filling, otherwise partial reflection of the cone will occur at small angles of incidence.

"Hard" and "Soft" Lens Options. - In the course of discussions, it has become apparent that there are two possible approaches to the solution of the problem of pressure tolerance in a Sea Urchin array. The pressure-bearing surface may be the outer surface of the lens (as in Fig. 6) which is then a more or less conventional pressure vessel. The PMT and its associated electronics inside the vessel need not be pressure-tolerant in this case, which we call the "hard" lens. Alternatively, the lens surface may be a thin skin of either glass or plastic, and the the PMT the pressure-tolerant element, as in Fig. 7. The electronics must then be pressure-tolerant as well.

Since both these options appear to be feasible, both must be explored until their relative advantages and disadvantages are thoroughly understood.

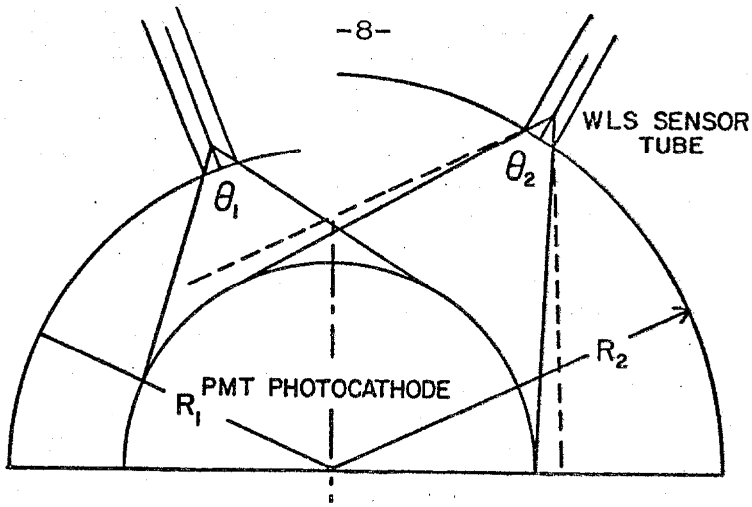
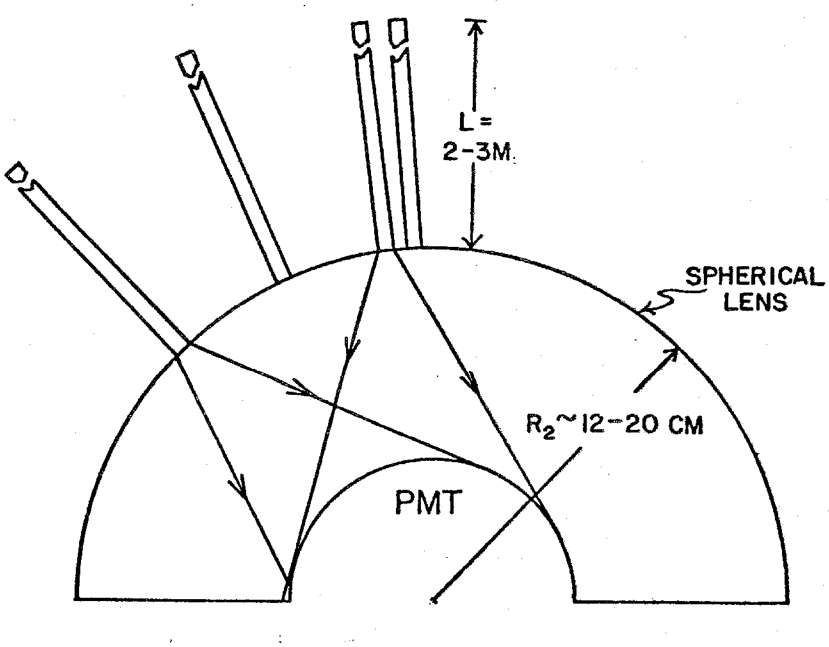


Fig. 4. The spherical lens. The inner hemisphere is the PMT photocathode, the outer surface is a hemispherical shell, glass or plastic. The transparent medium between determines the strength of the lens. In the left-hand portion of the figure, the lens filling and PMT glass envelope have the same index as the solvent filling the sensor tubes; the distance between inner and outer hemispheres is so chosen that the cone angle θ_1 of the emerging light just fills the PMT area. In the right-hand section, a higher index liquid is used; the cone angle θ_2 is now less than θ_1 (shown in dotted lines, and thus the outer hemisphere can have a larger radius, allowing more WLS sensor tubes to be used.



SEA URCHIN

Fig. 5. Sketch of the Sea Urchin Array. Only a few of the several hundred WLS tubes are shown. Tubes are 3m long, the lens 12-20 cm in radius, depending on the PMT diameter, which is 5" - 8".

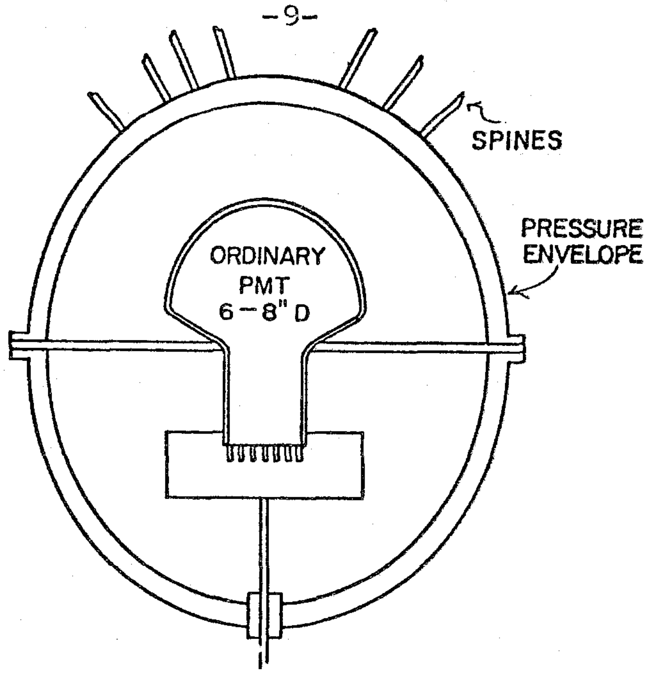


Fig. 6. The "hard" lens option. The PMT is enclosed in the pressure-bearing glass envelope; it and its associated electronics need not be pressure-tolerant. Penetrators for electrical leads are required.

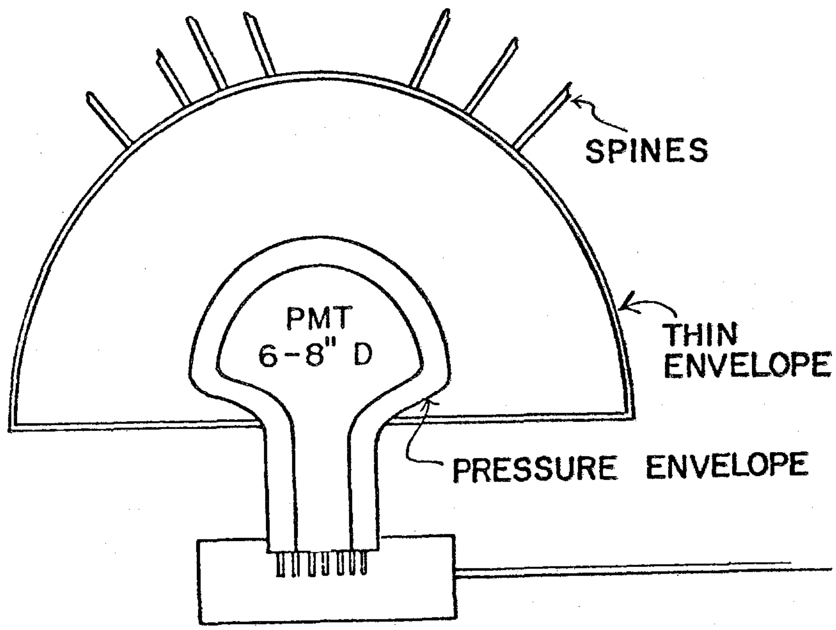


Fig. 7. The "soft" lens option. The spherical lens is a thin shell, and the pressure is borne by the envelope of the PMT. The electronics must also be pressure-tolerant.

6. SHADOWING AND THE EFFECTIVE AREA OF THE ARRAY.

The central region of the Sea Urchin module is crowded, and undoubtedly opaque in any dirction, if the spines are thought of as black to incident light. At the outer edge, the spines are some 10 to 20 diameters apart, and there are some directions in which light rays can pass through the module unimpeded. It is necessary to be able to calculate the effective absorbing area of the module as a function of direction. The CORONA program referred to above is insufficient for this purpose, since it does not take shielding or shadowing of one element by others into account. A modification of that program, called URCHIN, is presently in preparation. It is necessarily a complicated one, since it requires the location of each of the spines of the module. Pending its completion we can make some educated guesses.

In view of the opacity of the central region, it has been suggested (H. Bradner and J. Learned) that the spines might be internally divided by a transparent partition at some distance like 50-75 cm from the center, with the inner section containing only the solvent with no WLS. The effective 3m length would begin at that point, the inner section serving merely as a light pipe. This suggestion is predicated on the guess that without the WLS solute the solvent is highly transparent. Such design details must await experimental confirmation.

The limiting value of the effective area of the module is clearly the area of the 6m-diameter circle which is the diametral plane of the hemisphere enclosing the module. That limit applies to light normal to that plane; light parallel to it sees an area not more than half as great. Variations in shape to make the module more isotropic must await the completion of the URCHIN program.

7. TRANSPORT AND DEPLOYMENT PROBLEMS.

The Sea Urchin module, with tubes 3m long covering the spherical lens, occupies a hemisphere over 6m in diameter. With 18 such modules on a single string, the problem of transporting and deploying such a system is a serious one.

It appears reasonable to try to fold the array in some manner for transportation. Let us suppose that the spines are all inserted at their inner ends into a flexible sheet that allows the tubes to be secured in a parallel bundle for transport, and then fitted over the hemispherical lens surface when the string is deployed. A package of 3-400 tubes of 2-cm diameter can be packaged into a bundle under 18" in diameter. We can envisage the tubes so bound up for transport, and on deployment, when the strings are released from their cansiters, untied so that the spines open up like a flower, and the flexible sheet is secured to the lens surface. How this is to be done still requires considerable work.

TABLE 1. COMPARISON OF CYLINDRICAL WAVELENGTH-SHIFTER MODULES.

PROPERTY	1978 STANDARD MODULE		SEA URCHIN 5"PMT	6"PMT	8"PMT
Diam. of cyl.,cm	33.3		2.	2.	2.
No. of cyl./mod.	1		228	340	645
Cyl Length,m.	6		3.	3.	3.
Proj. Area, m^2 of cylinders	2.		13.	20.4	38.7
Estim. effective light interception area, m^2	2.		6.5	10.2	19.3
Solvent	Benzyl alcohol	Toluene	Toluene	Toluene	Toluene
Index of refr.	1.55	1.51	1.51	1.51	1.51
Volume of solvent/module	760 l.	760l.	143 l.	214 l.	406 l.
Mass of solv./ module,kg	813	684	129	193	365
In-water wt., kg.	53	-76.	-14.3	-21.4	-40.6
Tot. solv. mass,tons	18450	15525	2930	4380	8290
Solv. Cost,M$	40.6	4.56	.86	1.29	2.44
Incident light flux, quanta/m^2, to give 25 quanta at PMT cathode:	224	268	92	61	32
K^{40} background rate, sec^{-1}	6.3×10^4	$6.3 \cdot 10^4$	$1.02 \cdot 10^5$	$1.60 \cdot 10^5$	$3.03 \cdot 10^5$

(NOTE: This includes an estimate of shadowing, and may be in error by 25% or more.)

Since the module is nearly isotropic, except for light shielded by the core and PMT housing, it could in principle be oriented in any arbitrary direction to the string cable. Unfortunately, the axial location of the 1978 standard module does not seem to be available, since the PMT must occupy it.

8. SUMMARY

Table 2 gives a summary of the advantages and disadvantages of the Sea Urchin module as compared with the 1978 Standard.

Table 2. IMPROVEMENTS TO 1978 STANDARD WLS MODULE.

A. Advantages of proposed changes.

1. Nearly isotropic sensitivity to incoming light.
2. Increase in absolute light sensitivity.
3. Decrease in amount and cost of solvent used.
4. Decrease in number and cost of PMT's required; one 5"-8" tube per module now appears possible.
5. The module is now buoyant instead of requiring external buoyancy to be provided.
6. A mojor decrease in module cost is expected, which is partially offset by increased deployment costs. No figures available as yet.

B. Disadvantages of Proposed Changes.

1. More complex construction, more fragile sensor elements.
2. The elements of the new module will probably need to be transported in other than their final configuration, as noted above. This introduces an element of unreliability into the deployment process.
3. Toluene, although much cheaper than benzyl alcohol, is a less desirable pollutant in case of a spill or leakage.
4. There will probably be a considerable increase in the size (and cost) of canisters, and perhpas in the cost of deployment.
5. It no longer appears possible to consider the mechanical cleaning of glass elements as feasible, even in principle.

REFERENCES

1. A. Roberts and G. Wilkins, Chap. 2,Vol. 3, Proc 1978 DUMAND Summer Workshop, DUMAND, Scripps Institution of Oceanography, La Jolla, 1979.

2. N.B. Toluene has not yet been experimentally tested with acridine yellow for its WLS properties; it appears likely that it will be satisfactory. If not other WLS dyes are available.